Melting Domain Walls, NANOGrav Gravitational Waves and Dark Matter

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This talk is based on

- Beyond freeze-in: dark matter via inverse phase transition and gravitational wave signal
  e-Print: 2104.13722, PRD
- Gravitational shine of dark domain walls
  e-Print: 2112.12608, JCAP
- NANOGrav spectral index γ=3 from melting domain walls
  e-Print: 2307.04582, PRD
- Revisiting evolution of domain walls and their gravitational radiation with CosmoLattice
  e-Print: 2406.17053

Eugeny Babichev (IJCLab, Orsay)
Ivan Dankovsky (Moscow State U. and INR)
Dmitry Gorbunov (INR and MIPT, Moscow)
Sabir Ramazanov (ITMP, Moscow State U.)
Rome Samanta (INFN & SSM, Naples)
Alexander Vikman (CEICO, FZU Prague)

Main Message

- **Ultralight DM can be created for minuscular couplings and still produce observable GW**
- **NANOGrav GW can be from Melting Domain Walls of DM**

Z_2 -symmetric DM scalar field χ coupled to ϕ - a multiplet of N *thermal* degrees of freedom

portal coupling

$$V = \frac{1}{2}\left(M^2 - g^2\phi^\dagger\phi\right)\cdot\chi^2 + \frac{\lambda}{4}\chi^4 + \frac{\lambda_\phi}{4}\left(\phi^\dagger\phi\right)^2$$

tachyonic thermal mass

$$\mu^2 = g^2\langle\phi^\dagger\phi\rangle \simeq \frac{Ng^2T^2}{12}$$

increasing during preheating, then red-shifting

potential bounded from below

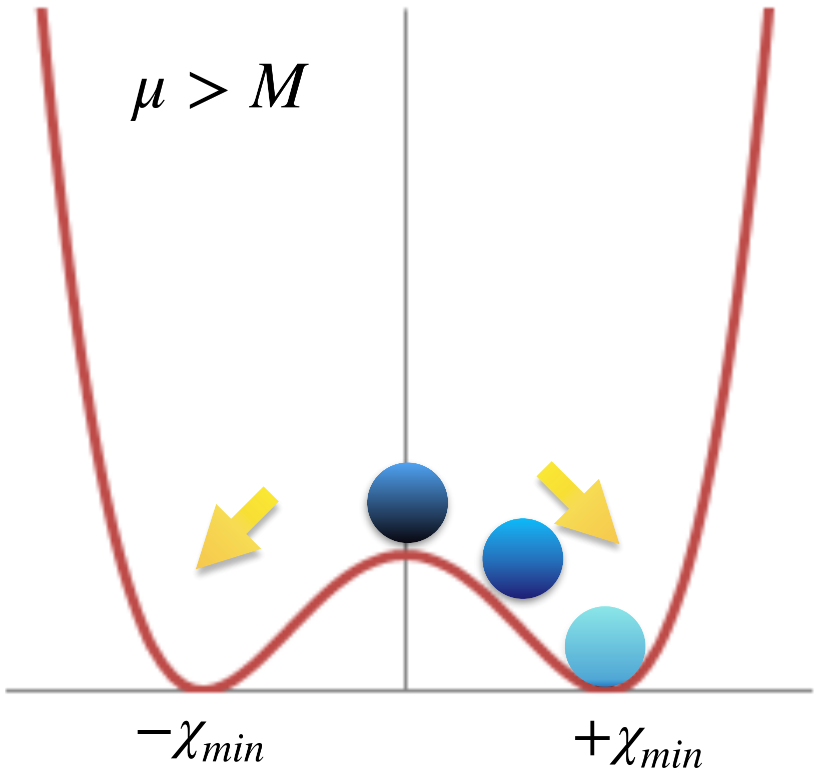
$$\beta = \frac{\lambda}{g^4} \geq \frac{1}{\lambda_\phi} \geq 1$$

potential bounded from below

weak coupling

Direct Phase Transition

Early universe spontaneously Broken Phase



Domain Walls!

Avoid too much friction to start rolling

$$\mu \gtrsim H$$

$$\sqrt{\frac{N}{12}}\, g T_i \simeq \sqrt{\frac{\pi^2 g_*}{90}}\frac{T_i^2}{M_{pl}}$$

$$T_i \simeq g\, M_{Pl}\sqrt{\frac{N}{g_*(T_i)}} \times \frac{1}{\sqrt{B}}$$

Correction taking into account time to get to the minimum

$$V_{eff} \simeq \frac{\lambda \cdot \left(\chi^2 - \eta^2\right)^2}{4} \qquad \eta(T) \simeq g\sqrt{\frac{N}{12\lambda}}\, T$$

Tension/energy per unit surface $\sigma_{wall} = \frac{2\sqrt{2\lambda}}{3}\eta^3(T)$ melting away as $\propto T^3$!

In the **scaling regime (Kibble 1976):** one domain wall per Hubble volume:

$$M_{wall} \sim \sigma_{wall}/H^2$$

$$\rho_{wall} \sim M_{wall}H^3 \sim \sigma_{wall}\, H \propto T^5$$

Usual Constant tension DW
$\rho_{wall} \propto T^2$

Scaling Parameter (constant tension DW)

Figueroa, Florio, Torrenti, Valkenburg

CosmoLattice

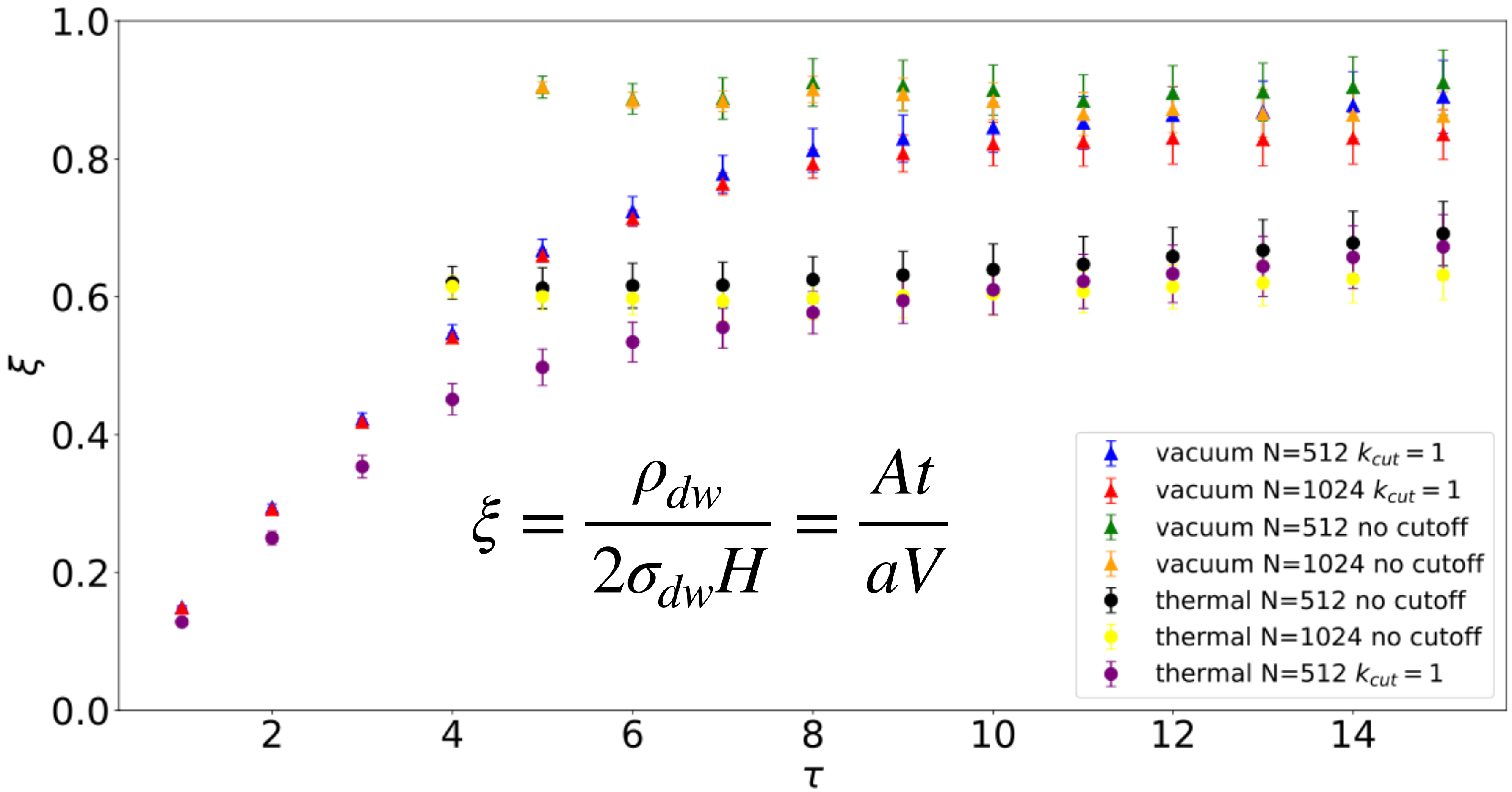


Figure 4: The area parameter ξ inferred in Eq. (44) is obtained from numerical simulations performed on lattices with the grid numbers $N = 512$ and $N = 1024$ starting from vacuum and thermal initial conditions with and without cutoffs at high momenta. Conformal time τ and conformal momentum k are in units of $\frac{1}{\sqrt{\lambda}\eta}$ and $\sqrt{\lambda}\eta$, respectively. The parameter ξ taking a constant value reflects that the domain wall network enters the scaling regime. Expectation values and error bars are obtained from 10 simulations run with different base seed values.

Dankovsky, Babichev, Gorbunov, Ramazanov, Vikman (2024)

Cf. Hiramatsu, Kawasaki, Saikawa (2013)

constant tension DW

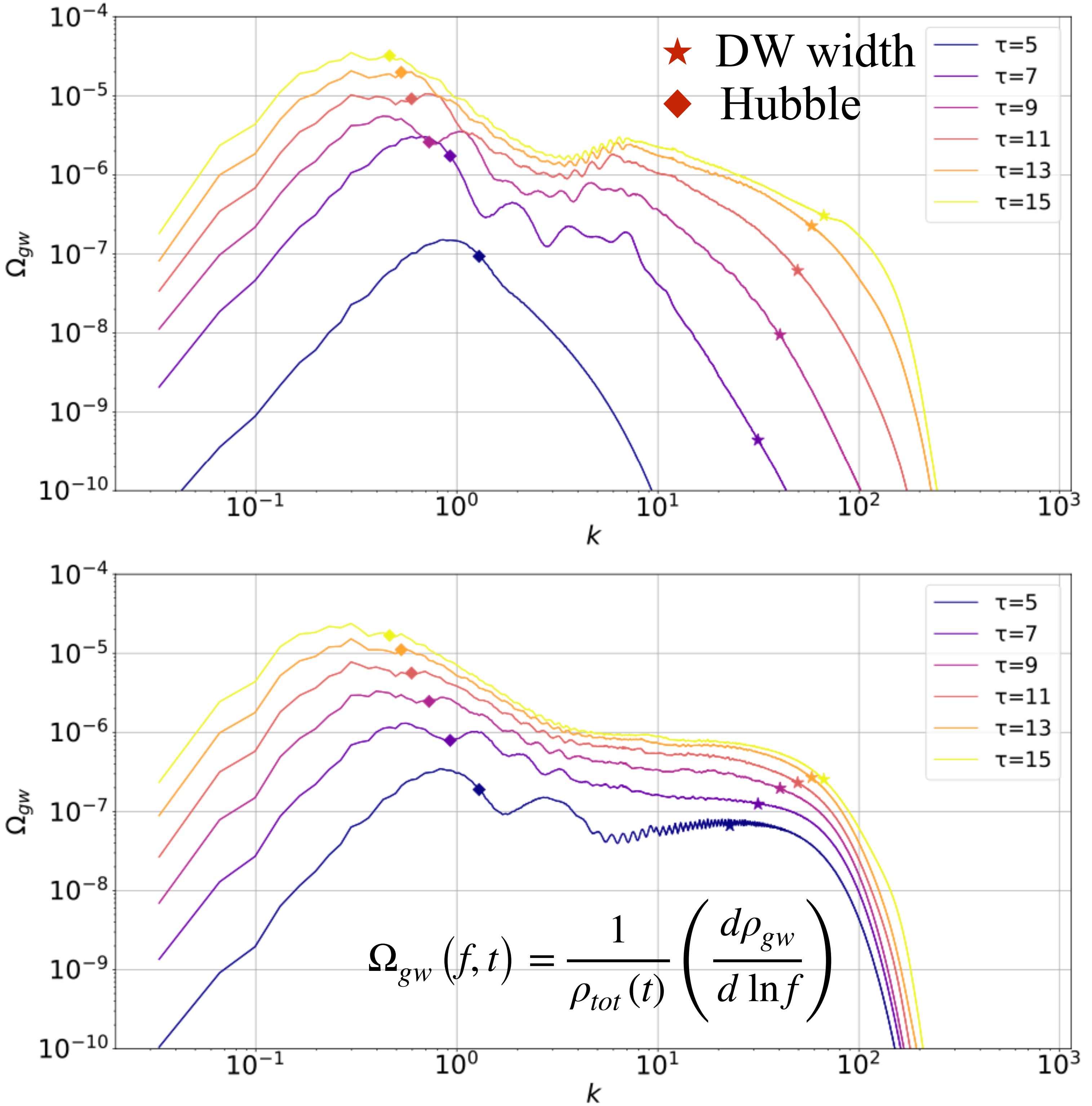


Figure 1: Spectrum of GWs emitted by the domain wall network at radiation domination starting with vacuum (top panel) and thermal (bottom panel) initial conditions defined in Eqs. (36) and (37), respectively. Conformal momenta and conformal times are in units of $\sqrt{\lambda}\eta$ and $\frac{1}{\sqrt{\lambda}\eta}$, respectively. The sharp upper cutoff at $k_{cut} = 1$ is applied in the case of vacuum initial conditions. The expectation value η is set at $\eta = 6\cdot 10^{16}$ GeV. Rescaling to arbitrary η is achieved by multiplying the spectra by $(\eta/6\cdot 10^{16}\ \text{GeV})^4$. Simulations have been performed on a lattice with a grid number $N = 2048$. The positions of diamonds correspond to the comoving Hubble scale $k = 2\pi Ha$ at the time associated with the corresponding curves, while stars show the inverse domain wall width $1/\delta_w$, i.e., $k = 2\pi a/\delta_w$.

Figueroa, Florio, Torrenti, Valkenburg

CosmoLattice

Dankovsky, Babichev, Gorbunov, Ramazanov, Vikman (2024)

cf.

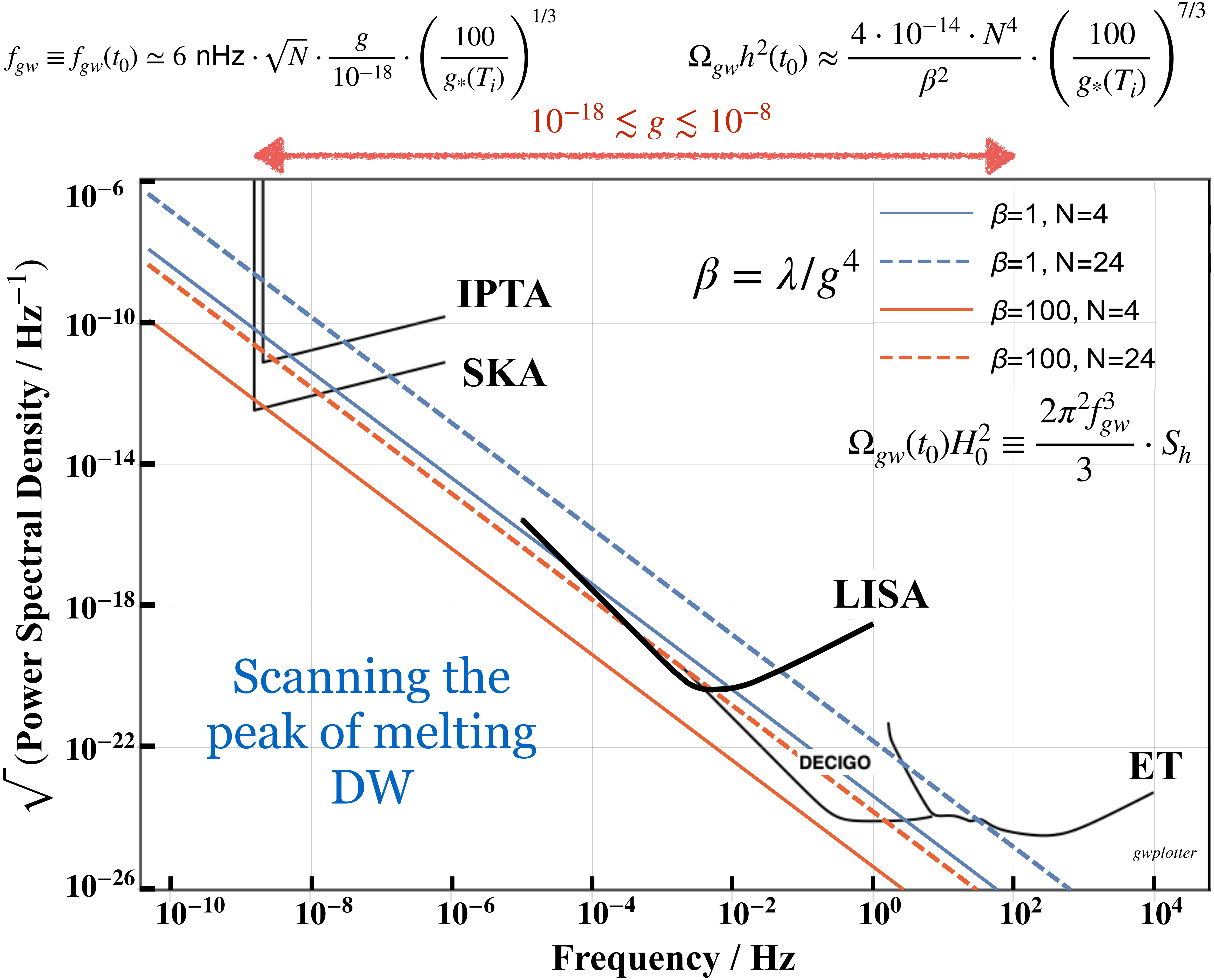
Hiramatsu, Kawasaki, Saikawa (2013)

Yang Li, Ligong Bian, Yongtao Jia; Yang Li, Ligong Bian, Rong-Gen Cai, Jing Shu (2023)

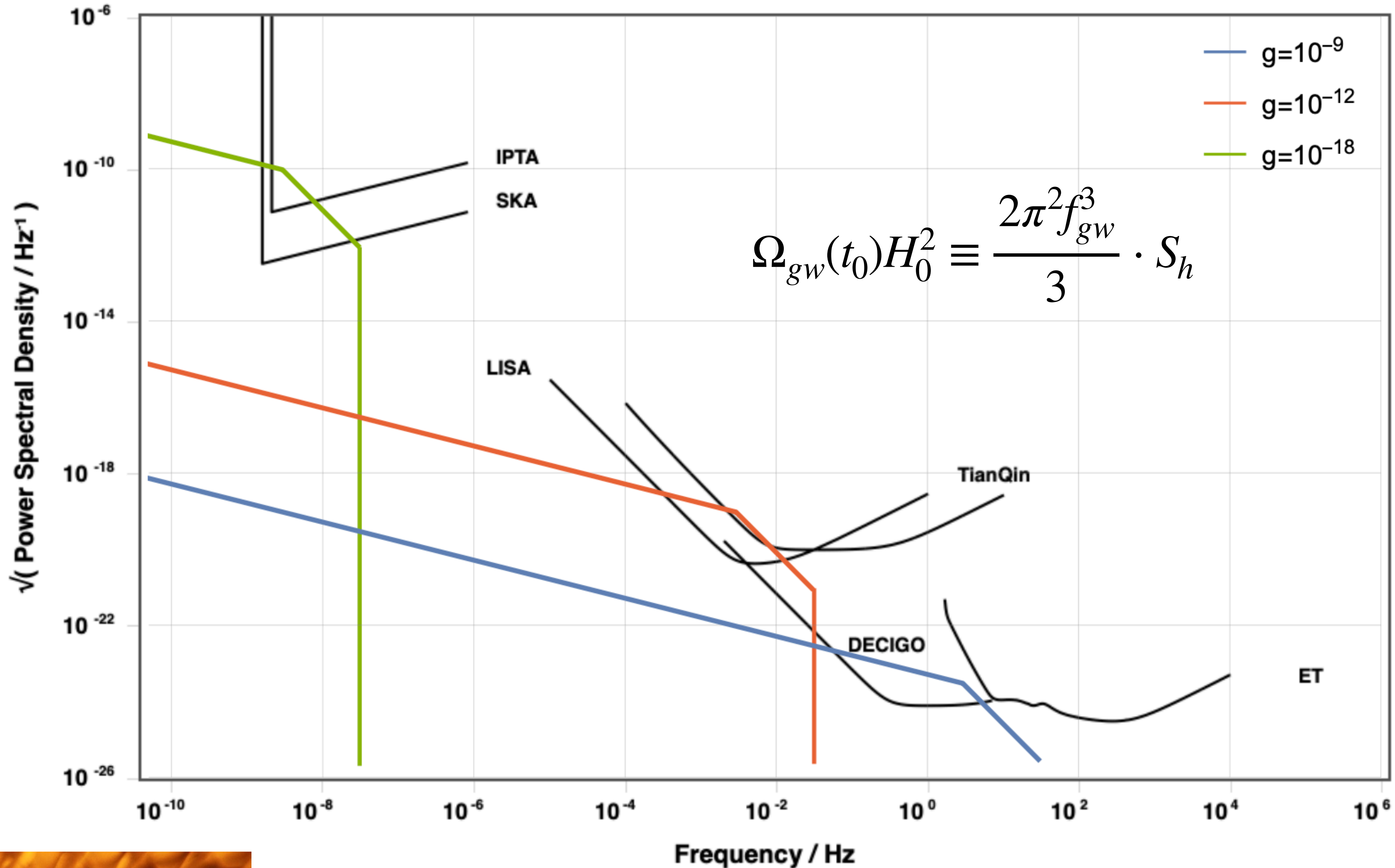
$$f_{peak} \simeq 0.7\, H_i \qquad f^0_{peak} \propto T_i$$

$$\Omega^{peak}_{gw} \sim \frac{\sigma^2_{dw}}{H_i^2} \propto \left(f^0_{peak}\right)^2$$

Melting Domain Walls



$f_{gw} \equiv f_{gw}(t_0) \simeq 6\ \text{nHz} \cdot \sqrt{N} \cdot \frac{g}{10^{-18}} \cdot \left(\frac{100}{g_*(T_i)}\right)^{1/3}$
$\Omega_{gw} h^2(t_0) \approx \frac{4 \cdot 10^{-14} \cdot N^4}{\beta^2} \cdot \left(\frac{100}{g_*(T_i)}\right)^{7/3}$
$10^{-18} \lesssim g \lesssim 10^{-8}$
$\beta = \lambda / g^4$
β=1, N=4
β=1, N=24
β=100, N=4
β=100, N=24
$\Omega_{gw}(t_0) H_0^2 \equiv \frac{2\pi^2 f_{gw}^3}{3} \cdot S_h$
IPTA
SKA
LISA
DECIGO
ET
Scanning the peak of melting DW
gwplotter
$\sqrt{(\text{Power Spectral Density / Hz}^{-1})}$
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency / Hz



$\Omega_{gw}(IR) \sim f^2$ $\quad$ $\Omega_{gw}(UV) \sim f^{-1}$ $\quad$ Cutoff $\ell = (\lambda/2)^{-1/2}\eta^{-1}$

Usual Domain Walls $\quad$ $\Omega_{gw}(IR) \sim f^3$

More on f^2 in IR

Dimensional analysis supported by simulation for constant tension

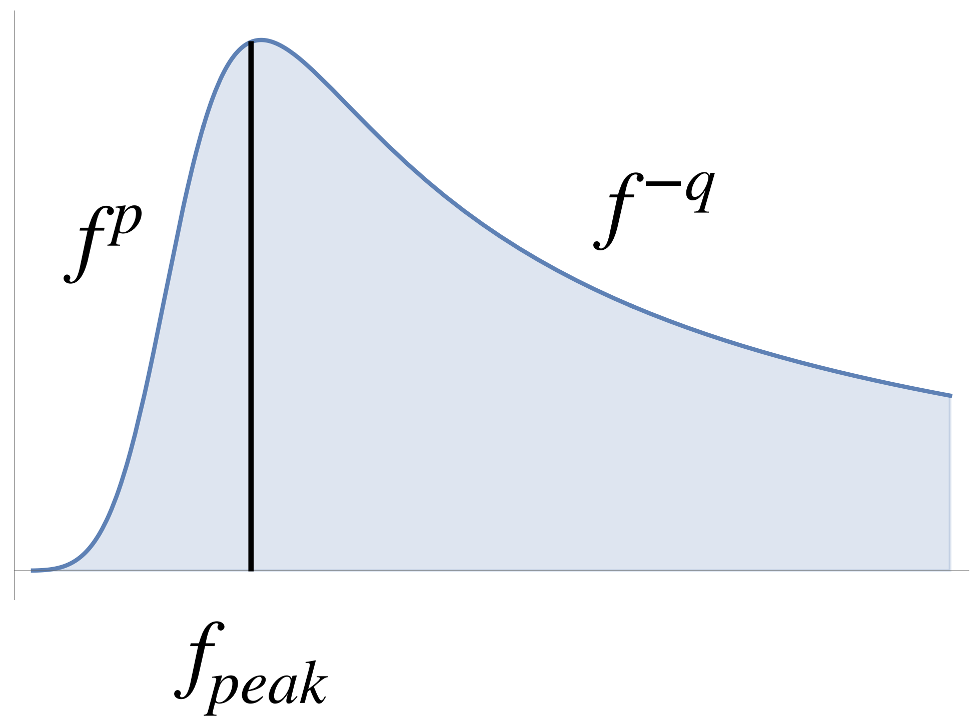
$$\Omega_{gw}(t_{now})_{peak} \simeq A \left(\frac{f_{peak}}{F_{max}}\right)^2$$

energy is additive

Σ over t_{em} = Σ over f_{peak}

$$\delta\Omega_{gw}(f) = 2A\left(\frac{f_{peak}}{F^2_{max}}\right)\delta f_{peak}\left(\frac{f}{f_{peak}}\right)^p \frac{2}{1+\left(f/f_{peak}\right)^{p+q}}$$

for $f_{min} \ll f \ll F_{max}$



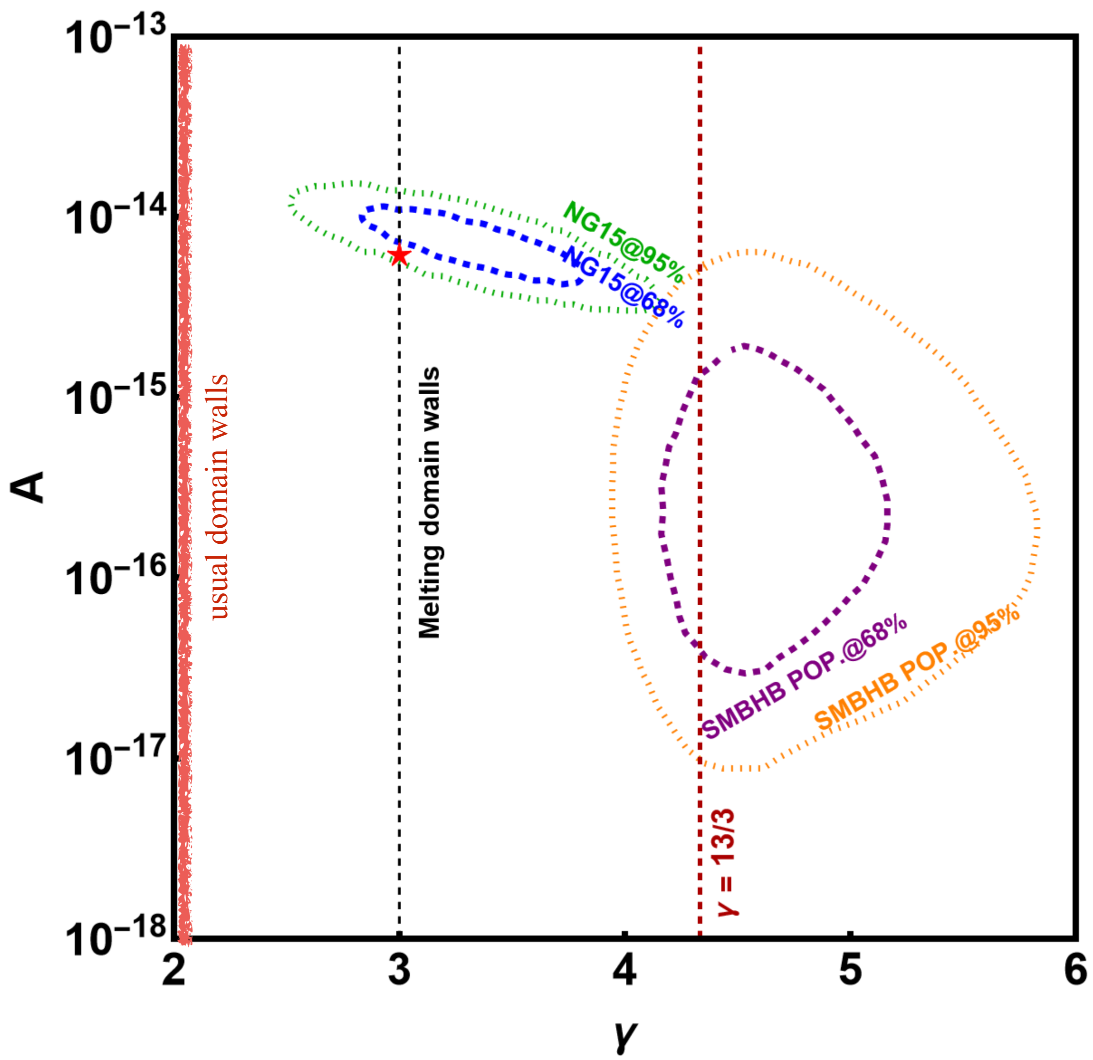
$$\Omega_{gw}(f) = \int_{f_{min}}^{F_{max}} \delta\Omega_{gw}(f) \propto \left(\frac{f}{F_{max}}\right)^2 \left[1 - \mathcal{O}\left(\frac{f}{F_{max}}\right)^n - \mathcal{O}\left(\frac{f_{min}}{f}\right)^m\right]$$

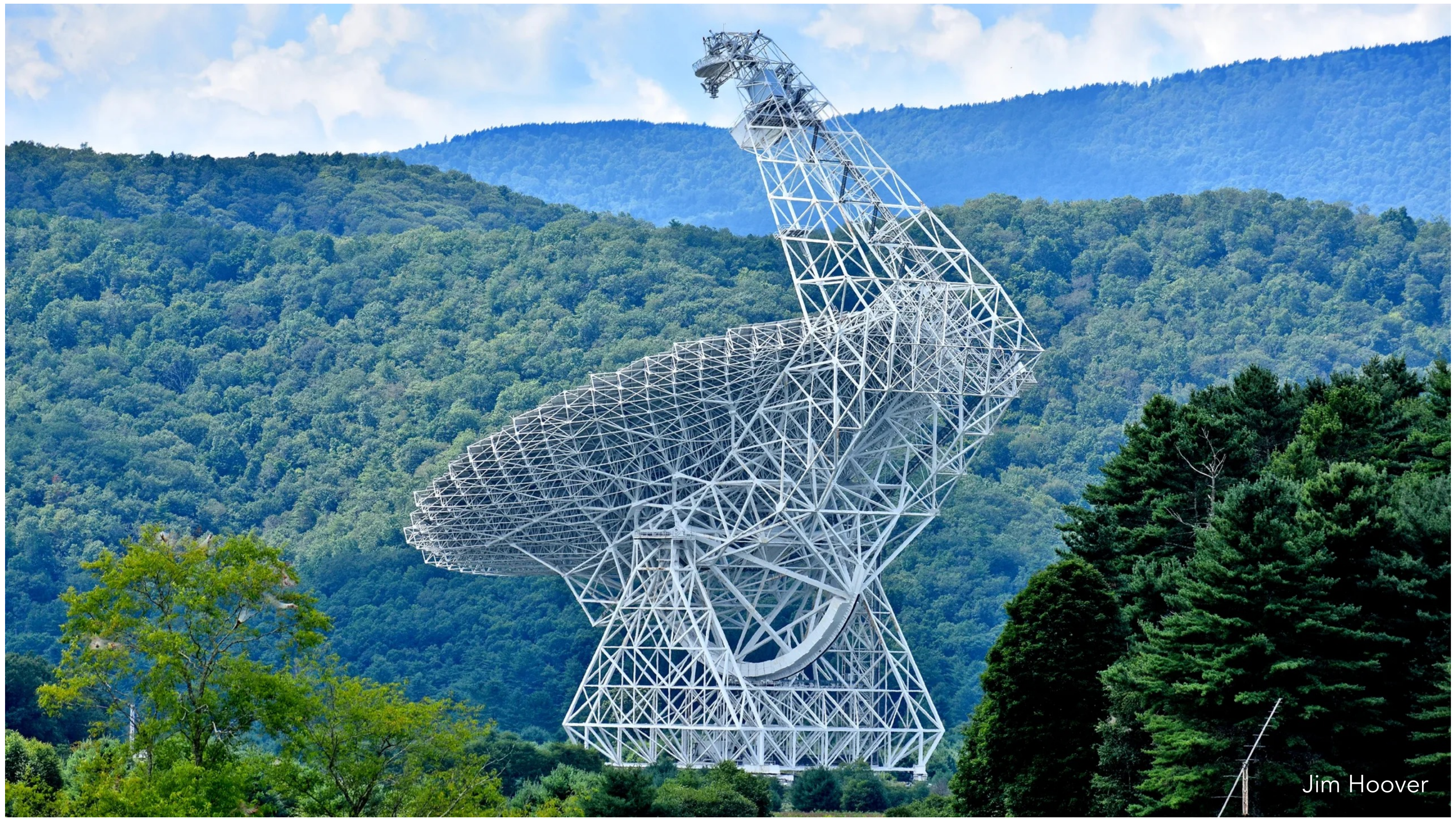
NANOGgrav

$$\Omega_{GW}(f) = \Omega_{yr}\left(\frac{f}{f_{yr}}\right)^{5-\gamma},$$

$$f_{yr} = 32\,\text{nHz}$$

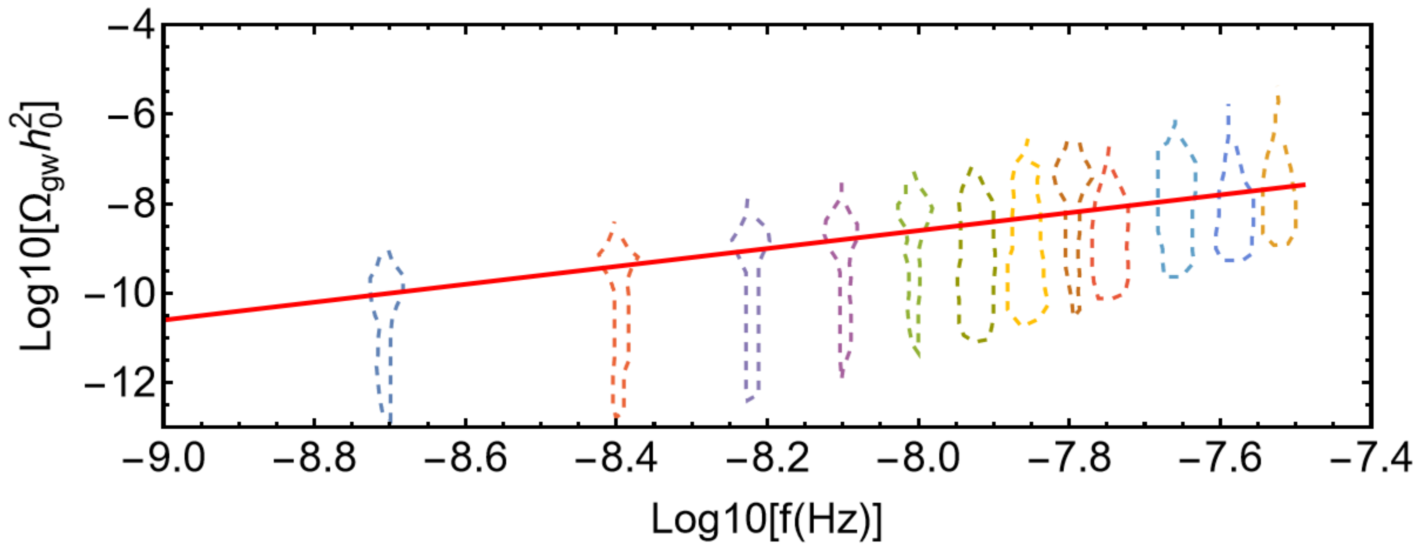
$$\Omega_{yr} = \frac{2\pi^2}{3H_0^2}A^2 f_{yr}^2$$





The 100-meter Green Bank Telescope, the world's largest fully steerable telescope and a core instrument for pulsar timing array experiment.

parameters $g = 10^{-18}$, $\beta = \lambda/g^4 = 1$, $N = 24$, $g_* = 75$

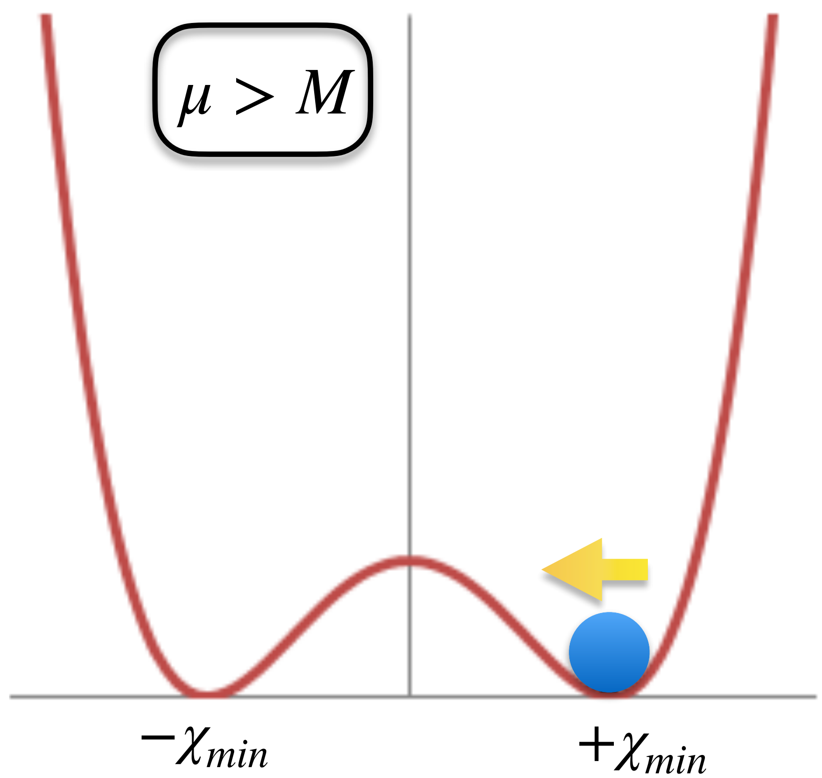


Inverse Phase Transition At Meltdown

$$\mathcal{L} = \frac{(\partial\chi)^2}{2} - \frac{\left(M^2 - \mu^2(t,\mathbf{x})\right)\cdot\chi^2}{2} - \frac{\lambda\chi^4}{4}$$

Early Universe

spontaneously Broken Phase with VEV slowly moving

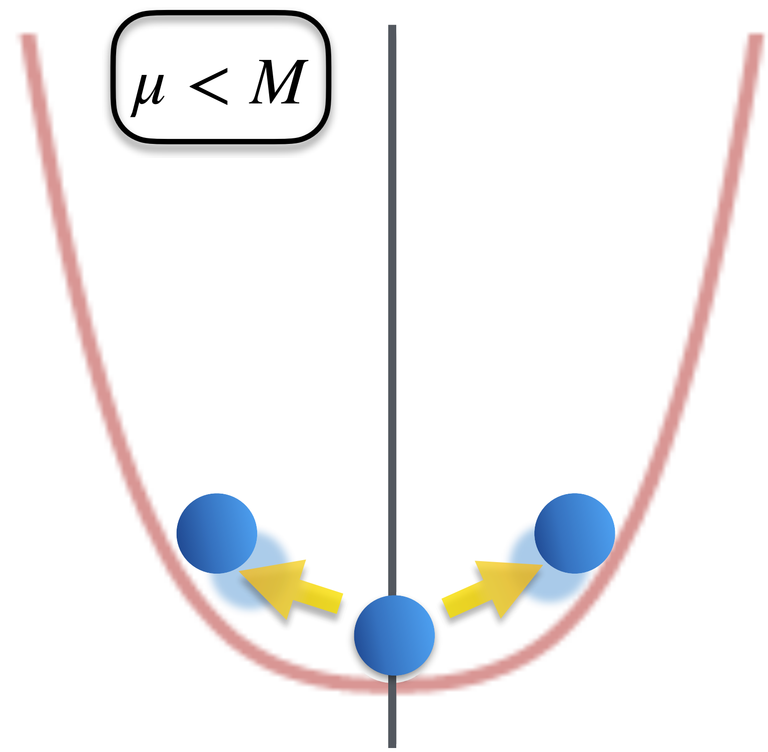


Tachyonic mass $\mu(t)$ slowly decreases / redshifts due to cosmological expansion

Late Universe

DW melt down and disappear

then oscillations around restored symmetric vacuum



for Hubble parameter

$H < M$

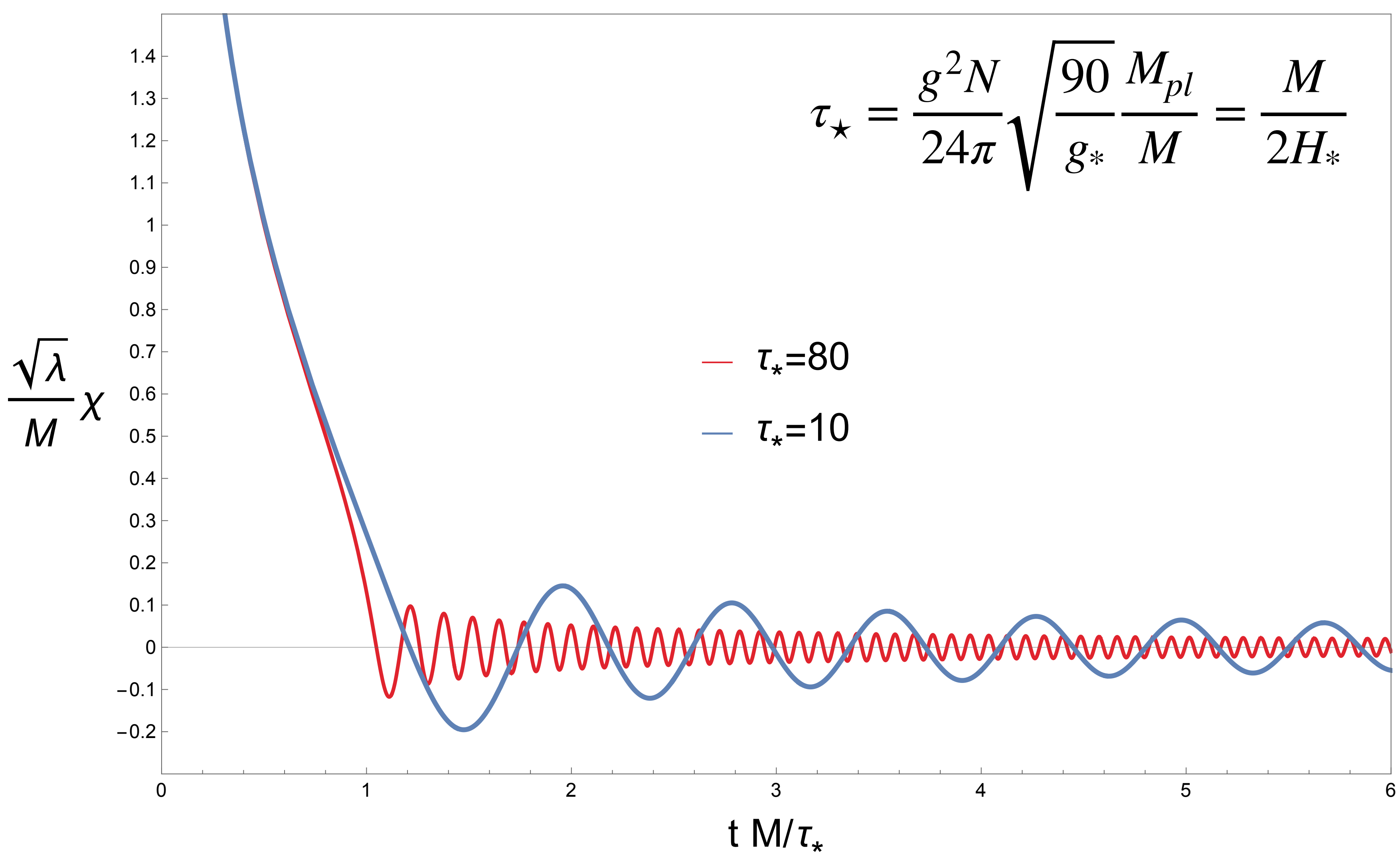
scalar field traces vacuum $\chi_{min}(t) = \sqrt{\frac{\mu^2(t) - M^2}{\lambda}}$ as long as $\left|\frac{\dot{M}_{eff}}{M_{eff}^2}\right| \ll 1$

Dynamics only depends on one single free dimensionless parameter

$$\ddot{\chi} + 3H\dot{\chi} + \left(M^2 - \frac{g^2 N T^2}{12}\right)\chi + \lambda\chi^3 = 0 \quad \text{with} \quad H = \frac{1}{2t} = \sqrt{\frac{\pi^2 g_*}{90}}\frac{T^2}{M_{pl}}$$

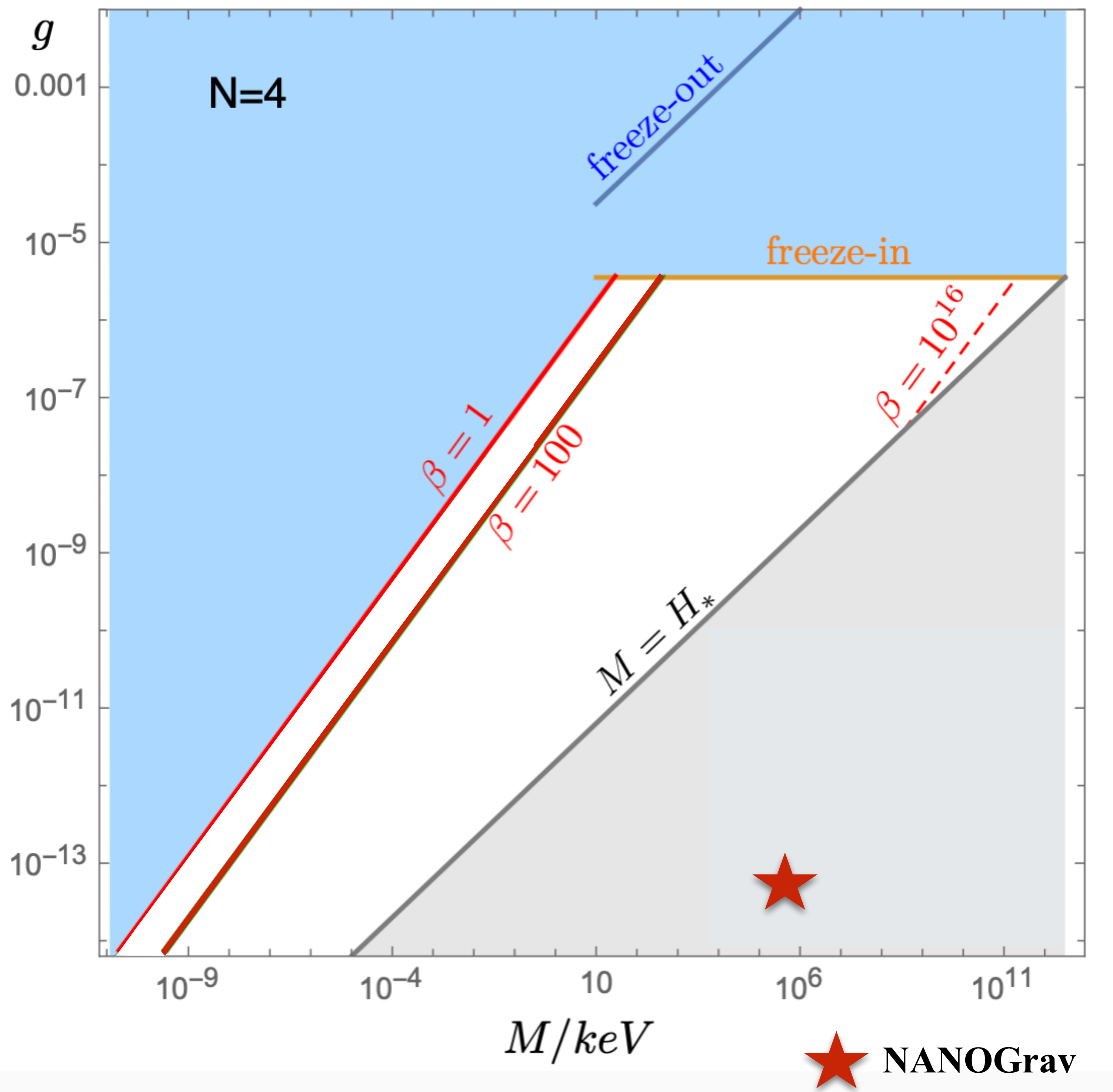
$$\frac{1}{\tau_\star^2}\left(\bar{\chi}'' + \frac{3}{2}\frac{\bar{\chi}'}{\tau}\right) + \left(1 - \frac{1}{\tau}\right)\bar{\chi} + \bar{\chi}^3 = 0$$

$$\tau_\star = \frac{g^2 N}{24\pi}\sqrt{\frac{90}{g_*}}\frac{M_{pl}}{M} = \frac{M}{2H_*}$$



Allowed Parameter Space

$$M \simeq \ 10^{-13}\ \text{eV} \cdot \frac{\beta^{3/5}}{\sqrt{N}} \cdot \left(\frac{g_*(T_*)}{100}\right)^{2/5} \cdot \left(\frac{g}{10^{-18}}\right)^{7/5}$$



A bridge between NANOGrav and LIGO!

DM from the inverse phase transition

$$M_\chi \simeq 10^{-12}\ \text{eV} \cdot B^{9/20} \cdot \left(\frac{g_*(T_{sym})}{100}\right)^{1/5} \cdot \left(\frac{g_*(T_i)}{100}\right)^{1/20} \cdot \left(\frac{m_\phi}{10\ \text{MeV}}\right)^{1/2} \times \left(\frac{f_{peak}}{30\ \text{nHz}}\right)^{6/5} \cdot \left(\frac{10^{-8}}{\Omega_{gw,peak}h_0^2}\right)^{3/20}$$

Superradiance for $M_{BH} \simeq 10^2 M_\odot$ → LIGO

Thanks a lot for attention!